

9th CCMC Community Workshop
April 23-27, 2018 • College Park MD, USA

Session: *International Forum for Space Weather Capabilities Assessment I*

Medium Range Thermosphere-Ionosphere Storm Forecasts

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U Michigan

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Thanks to: CCMC

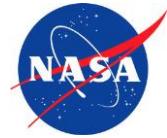
Aaron Ridley, U Michigan

The Model Development Community

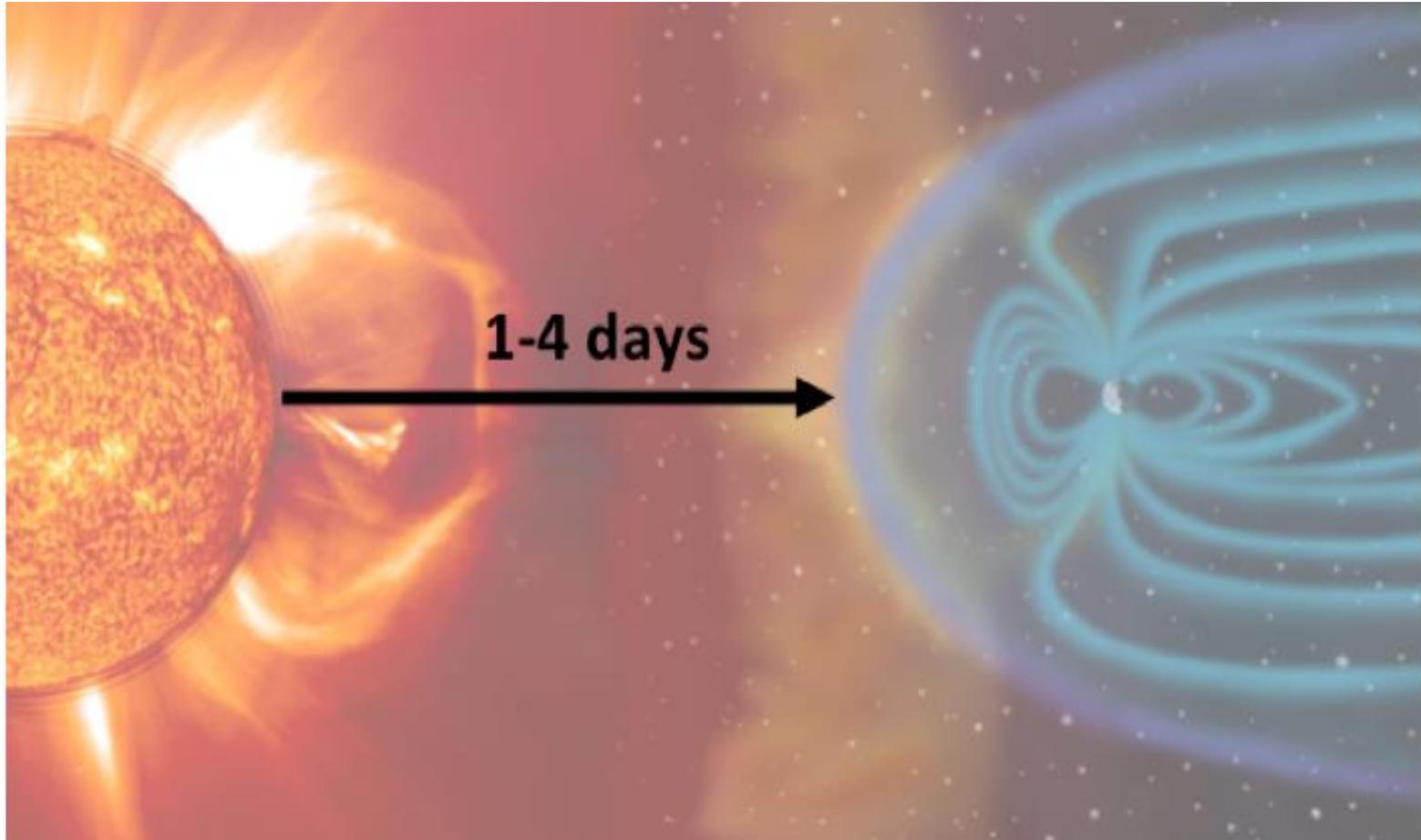


Overview

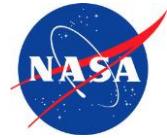
- **The vision: forecasting as a *scientific frontier***
 - **Understanding thermosphere-ionosphere storm forecasts**
 - **The Space Weather Forecast Testbed (SWFT)**
-
- **Acknowledgement: Lutz Rastaetter, Ja Soon Shim and Michelle Mendoza of CCMC**
 - **Web interface to SWFT and custom “forecast mode” runs**



Medium-Range Forecast



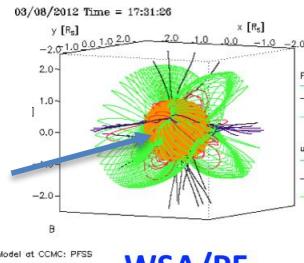
- The applied community has clearly stated a need for forecasts with such lead times
- Contrast to lead times based on ACE data (satellite at L1) of about 1 hour



Exploring “Sun to Mud” Forecasts

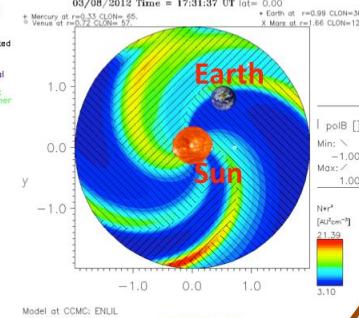
Solar
Interior

Solar Corona



WSA/PF

Heliosphere



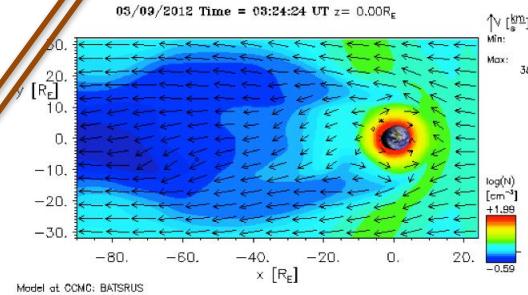
ENLIL

- Center for Integrated Space Weather Modeling (2000's), LWS TR&T, NSF, MURI, etc.
- NASA/NSF Partnership for Collaborative Space Weather Modeling (2013-)

Current solar wind
collaborators:
CSEM (U Michigan)
CCMC

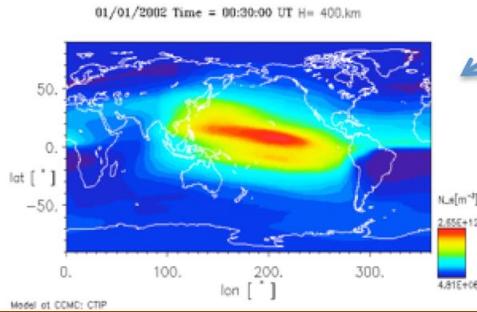
Operational

Magnetosphere

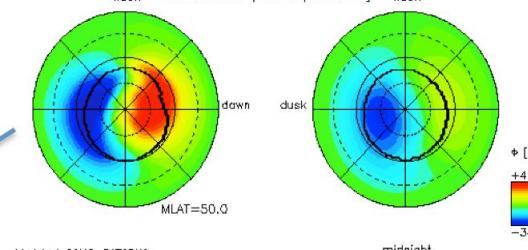


Our focus

Global thermosphere-
ionosphere storm



Northern Hemisphere Southern Hemisphere
noon solid contour: polar cap boundary noon



High latitude
convection pattern

Non-MHD:

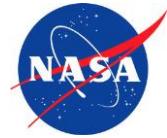
- Particle precipitation/aurora (empirical model)
- Shielding currents (Rice Convection M)



Ionosphere-Thermosphere Forecasts: A Scientific Frontier

- Existing simulations of the IT contain the essential physics of a global ionospheric storm
- Forecasts constitute the most rigorous tests of the simulations
 - Learn the implications of poorly observed simulation parameters
- In what ways do existing simulations differ from the output of a perfect simulation (aka observations*)?
 - What physics is insufficiently represented?
 - What are the impacts of poorly specified boundary conditions?
 - Forecasting context – useful!

*Filtered and noise added



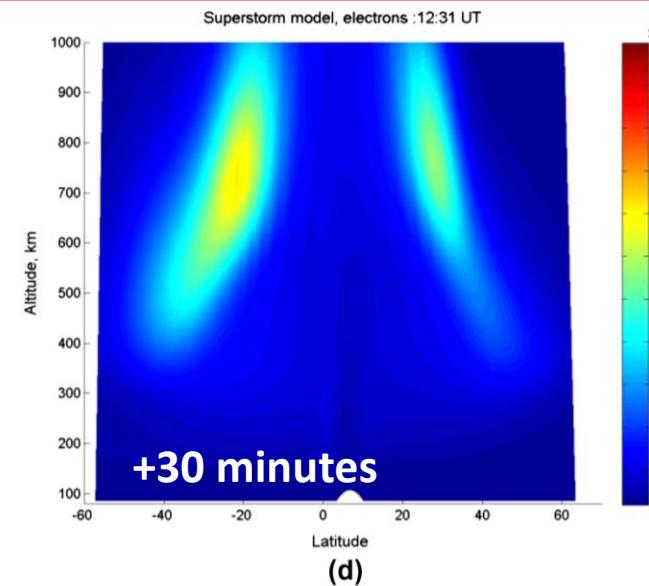
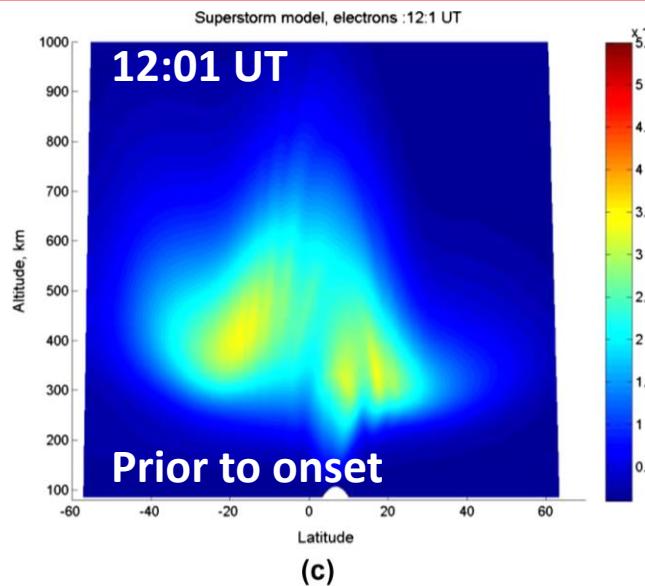
Simulating the Positive Phase of a Global Ionospheric Storm

20 mV/m for
1 hour

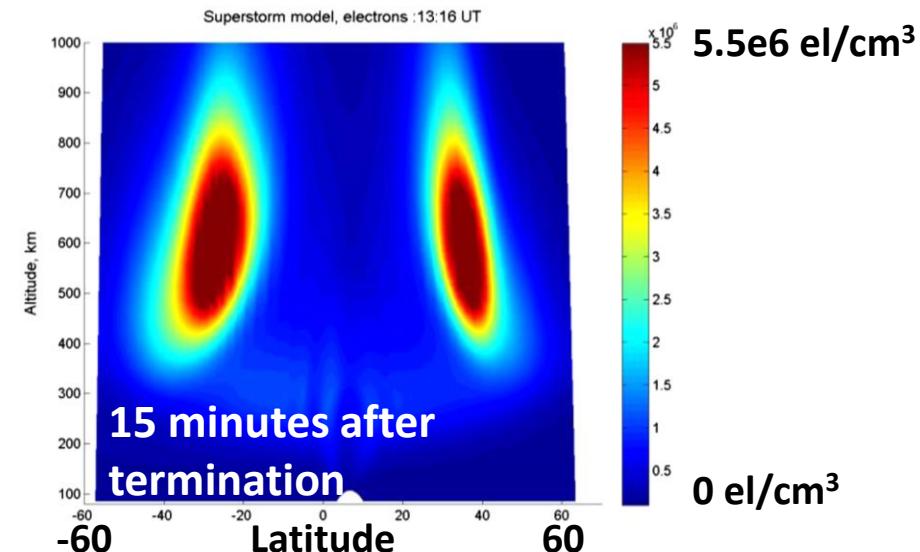
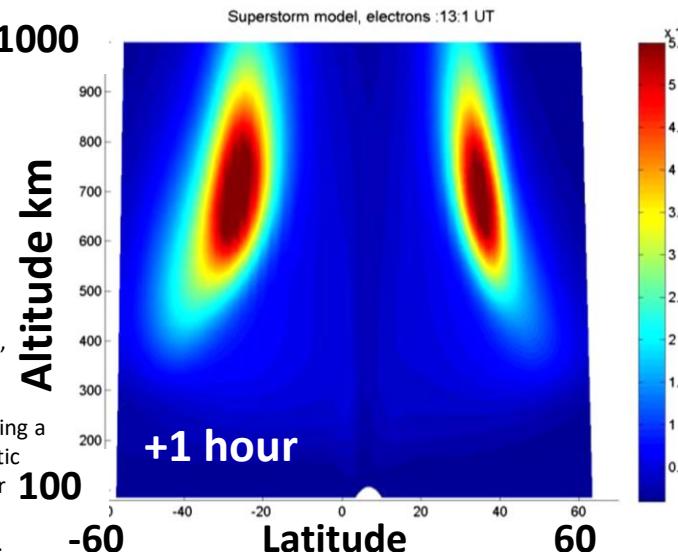
Estimate based on
inner
magnetosphere
estimate/
extrapolation

SAMI-2:
neutral wind
and
composition
unchanged
from quiet
time

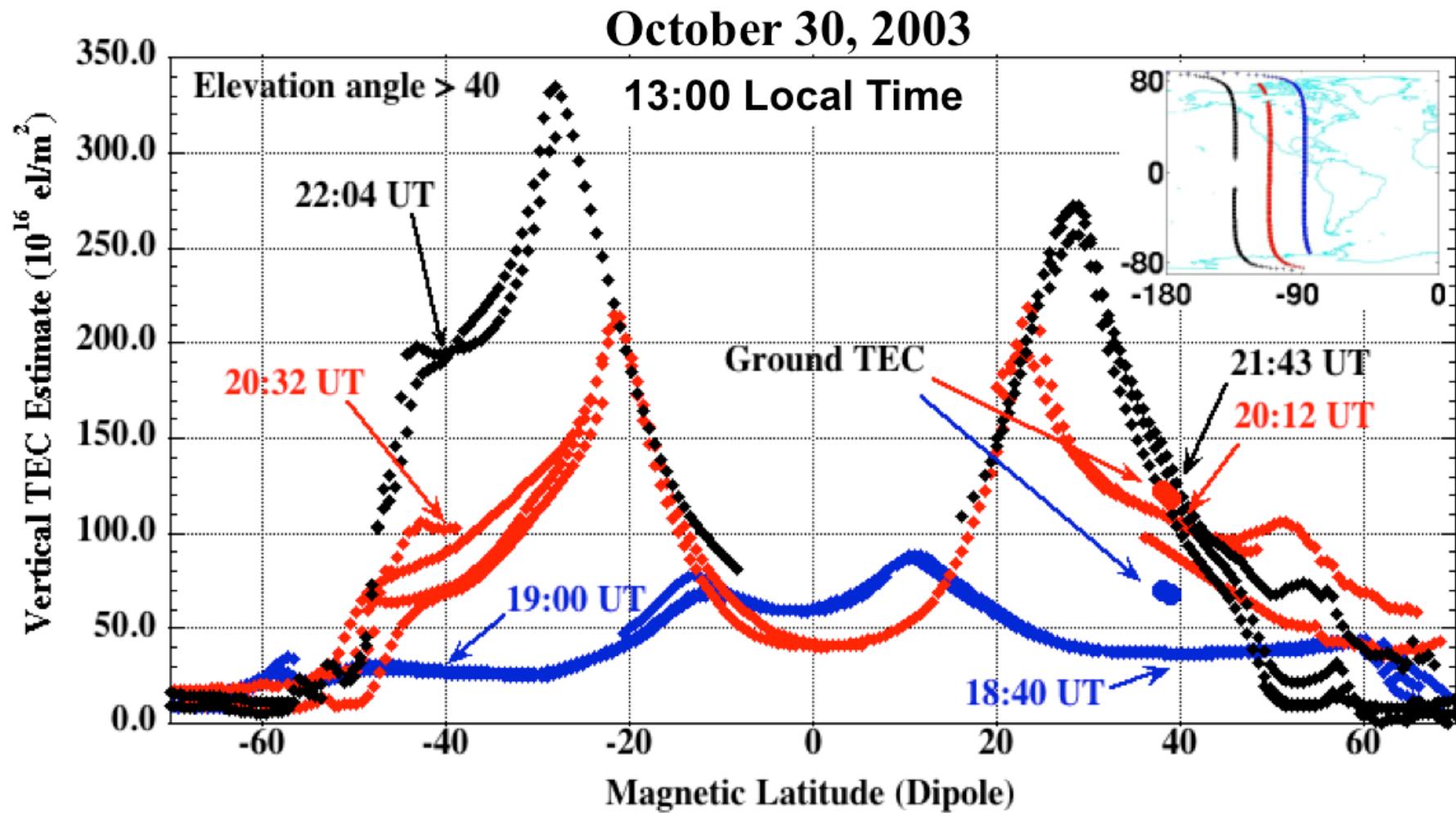
Tsurutani, B. T., O. P.
Verkhoglyadova1, A. J.
Mannucci, G. S. Lakhina,
and J. D. Huba (2012)
Extreme changes in the
dayside ionosphere during a
Carrington-type magnetic
storm, *J. Space Weather
Space Clim.* doi:
10.1051/swsc/2012004.



Winds are
“nominal”
poleward



The 2003 Halloween Superstorm



CHAMP altitude: 400 km

Mannucci et al., "Dayside global ionospheric response ..." *GRL* 2005

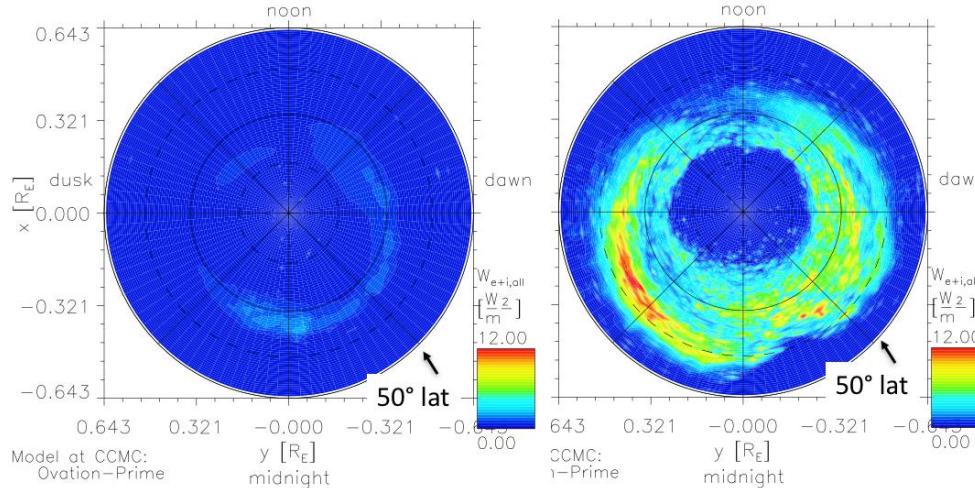


Forecast Mode Runs

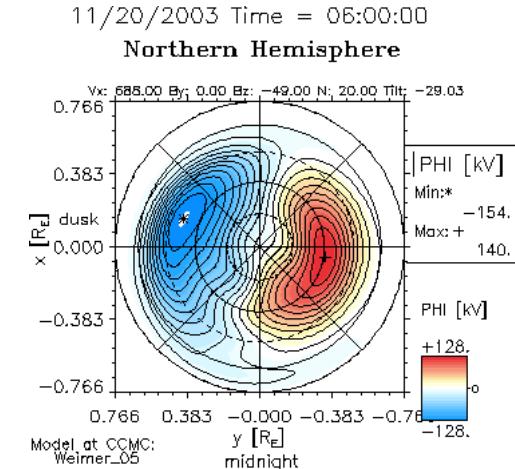
Example: Forecasting global ionospheric total electron content (TEC) – one of the simplest ionospheric quantities to forecast.

“Forecast mode” inputs:

- F10.7 EUV proxy
- Solar wind from OMNI data or [ENLIL](#), [CORHEL](#), [SWMF](#) heliosphere model runs
- Weimer 2005 empirical model of ionospheric electrodynamics
- Ovation Prime empirical auroral patterns



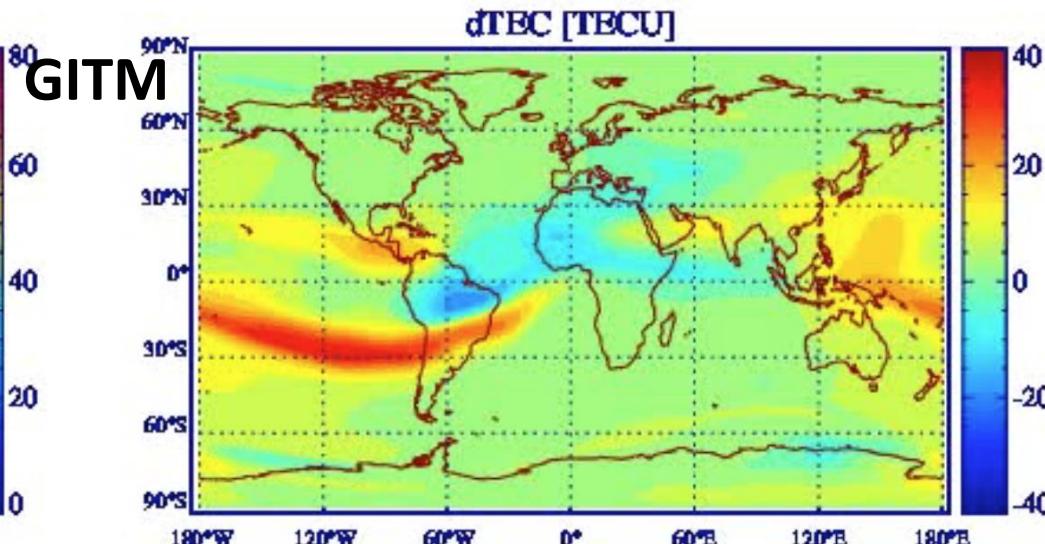
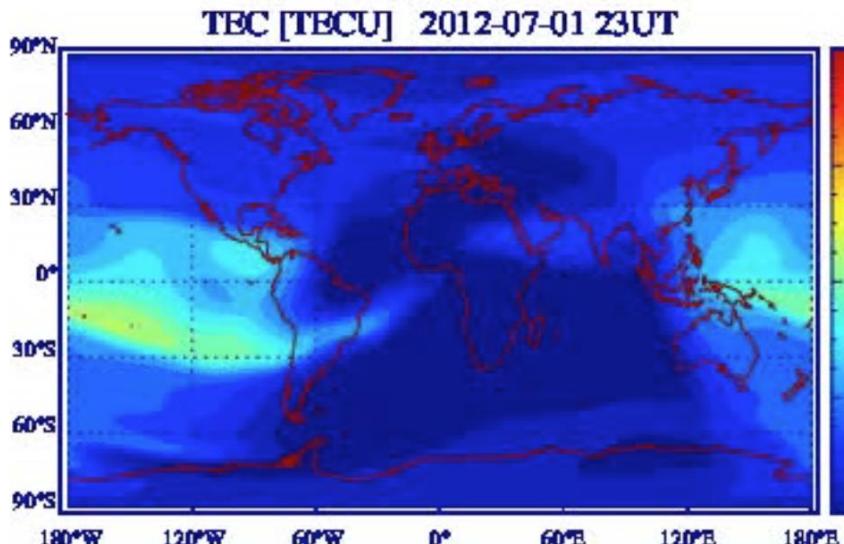
Ovation Prime particle precipitation model



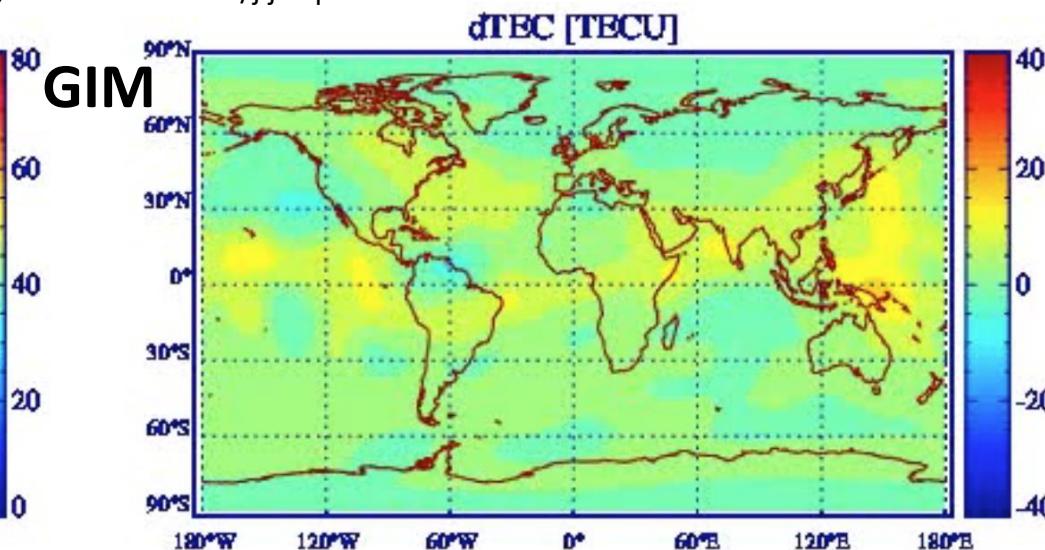
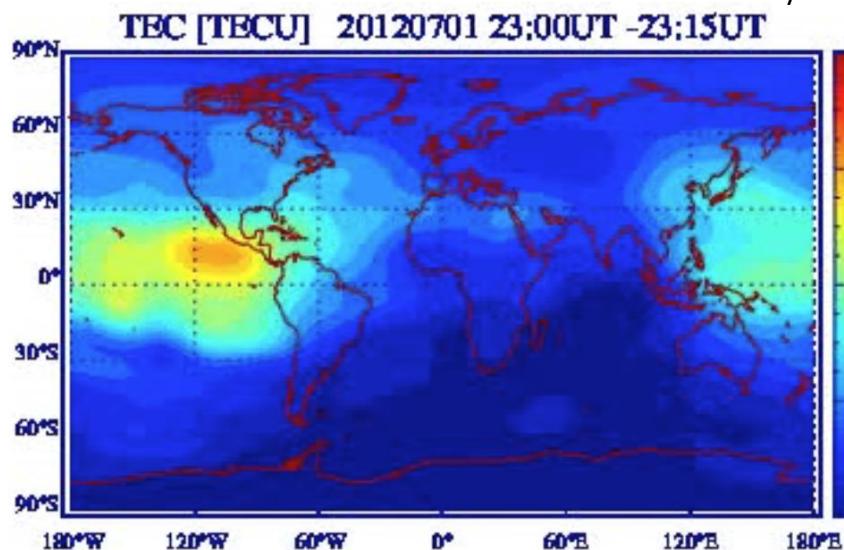
Weimer potential (convection)



Basis For Evaluation: Global Ionospheric Maps



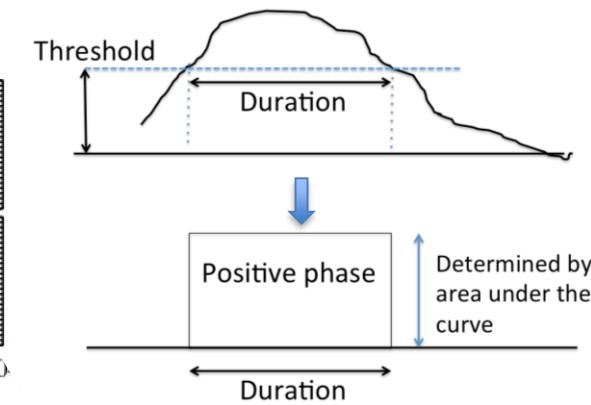
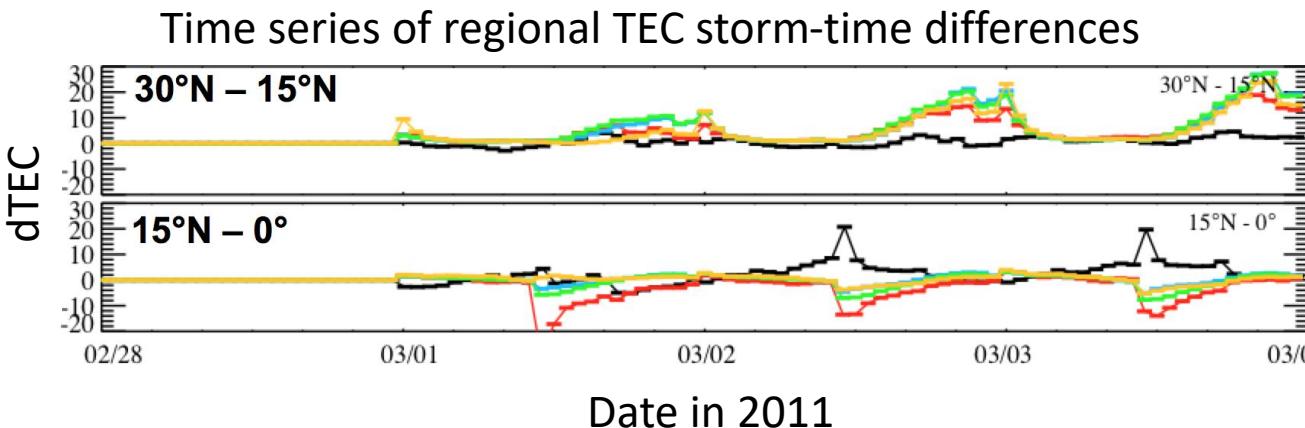
Ridley et al., 2006 doi:10.1016/j.jastp.2006.01.008



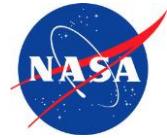


Physically Meaningful Model Output: “Forecast Variables”

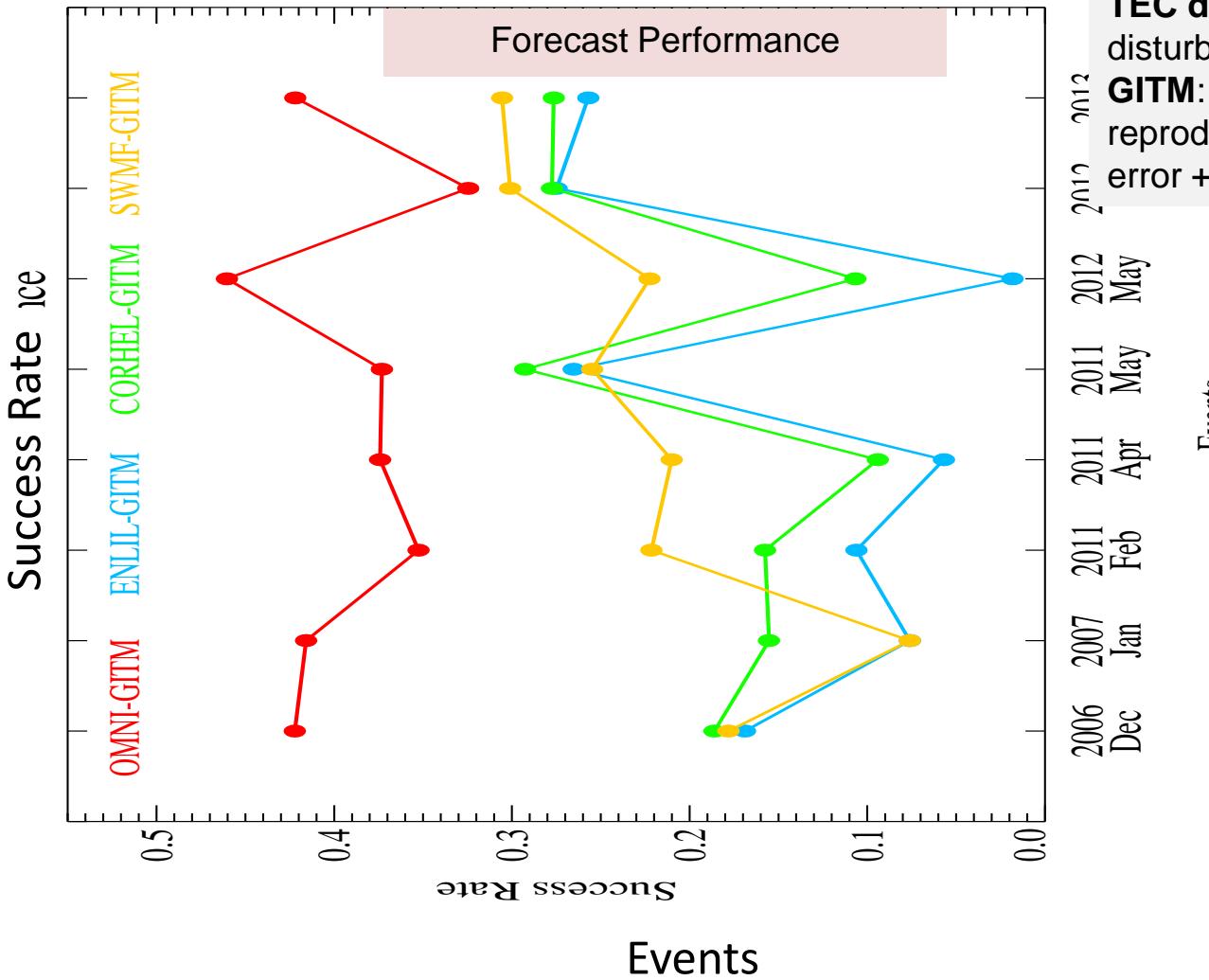
- Capture regional “positive” (TEC increases) and “negative” (decreases) *TEC changes relative to quiet time (dTEC)*
- Statistical significance based on quiet time variability
- Define a threshold level
- Take duration into account
- Compare global TEC map (“data”) to GITM output



See Meng et al., 2016, doi:10.1051/swsc/2016014



Solar Wind Driven “Forecasts”

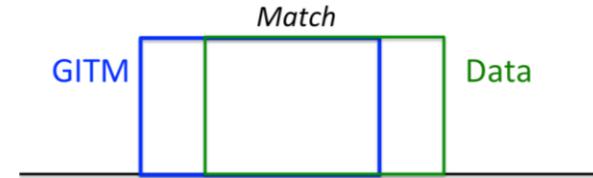


TEC data (GIM): number of all TEC disturbances with $|d\text{TEC}| > 4$
GITM: number of GIM TEC disturbances reproduced by the simulations, with time error +/- 3 hours at most

Forecast Success Rate:

$$\frac{\# \text{GITM Matches}}{\# \text{GIM TEC Disturbances}}$$

- Forecast variables are useful and will continue to be refined. Including adaptive location, thresholds, scaling, etc.





The Space Weather Forecast Testbed

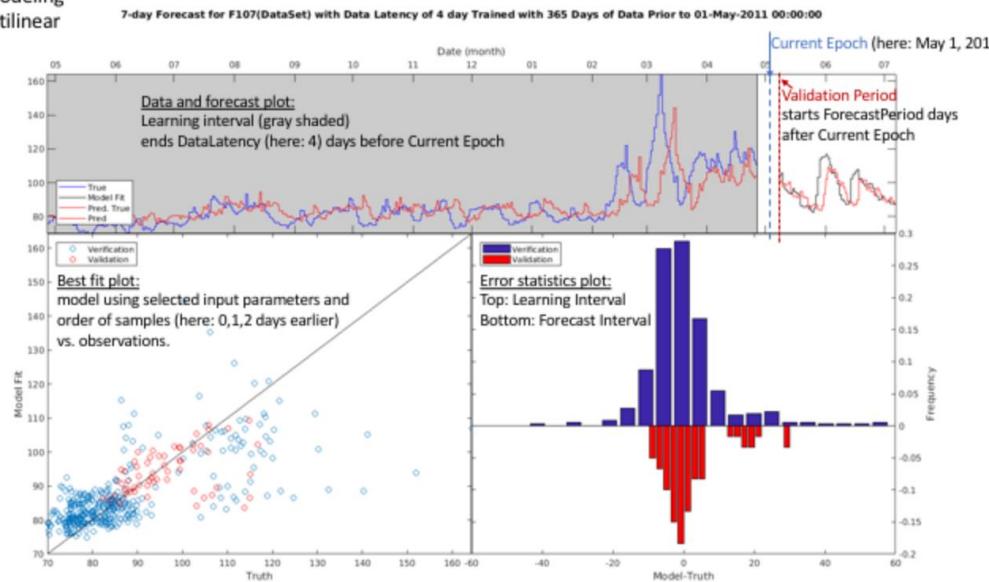
- **The Space Weather Forecast Testbed (SWFT) is a platform for assessing space weather forecast strategies**
- **Three key components of SWFT are:**
 - Repository of 12 years of solar, interplanetary, geomagnetic, ionosphere data and indices at 3 hour resolution
 - Matlab scripts that prepare data for forecast strategy training experiments
 - CCMC developed web-portal to allow web access and computation support
- **SWFT is currently at the beta stage**



Planned implementation as CCMC “Instant Run”

Sample plot of SWFT modeling and multilinear analysis

SWFT modeling
and multilinear
analysis



(The example shows the different time periods. The resulting forecast model can be improved.)

SWFT model instant run submission

Current Epoch (the start of the learning interval through the end of the forecast period must be between 2000/08/01 01:00 UT and 2012/12/31 23:59 UT):

- Year:
- Month:
- Day:

Data latency [days] (day of latest available data before current day during forecast):

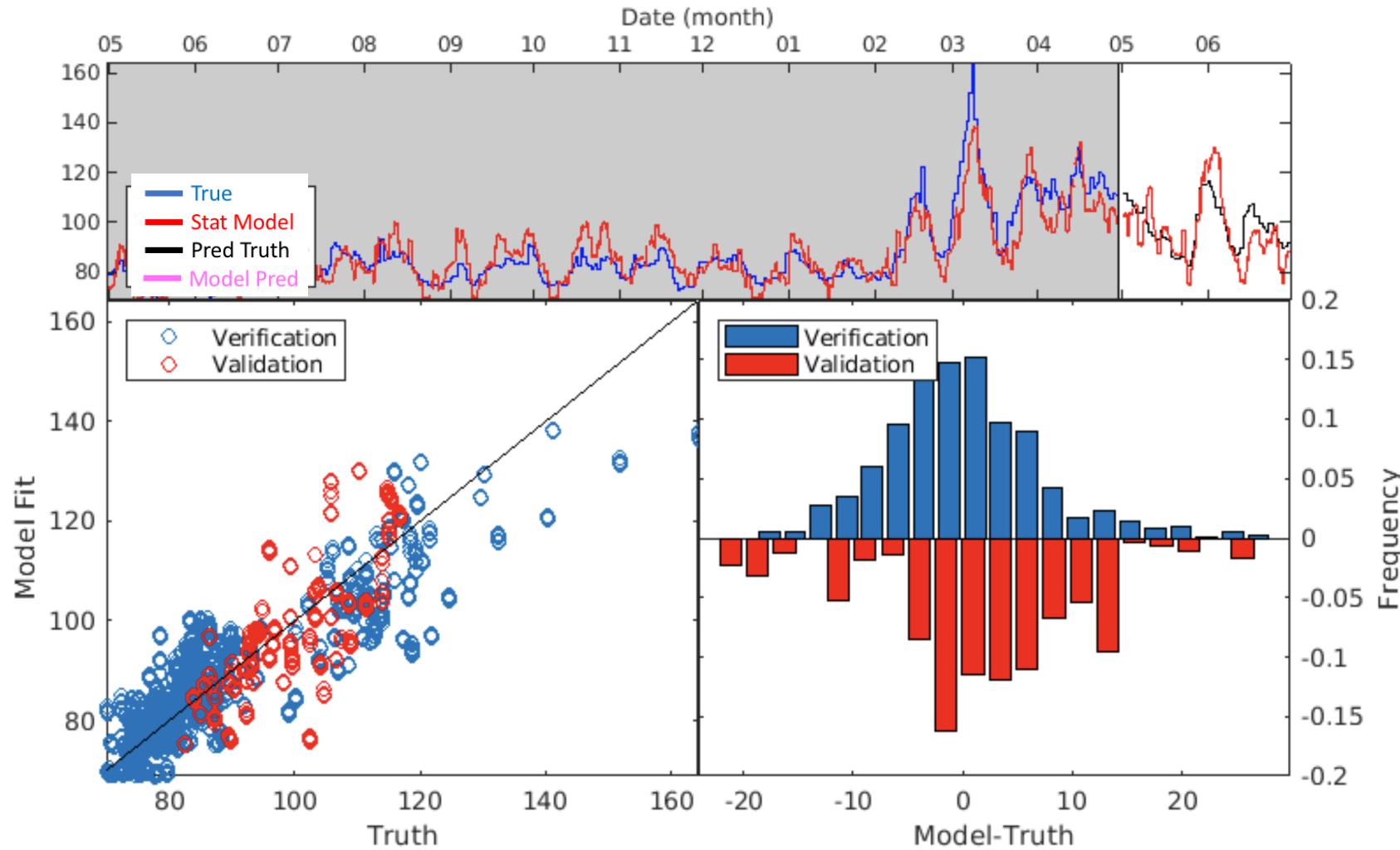
Learning Interval [days]:

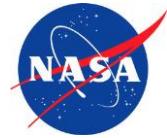
Instant Run interface for SWFT



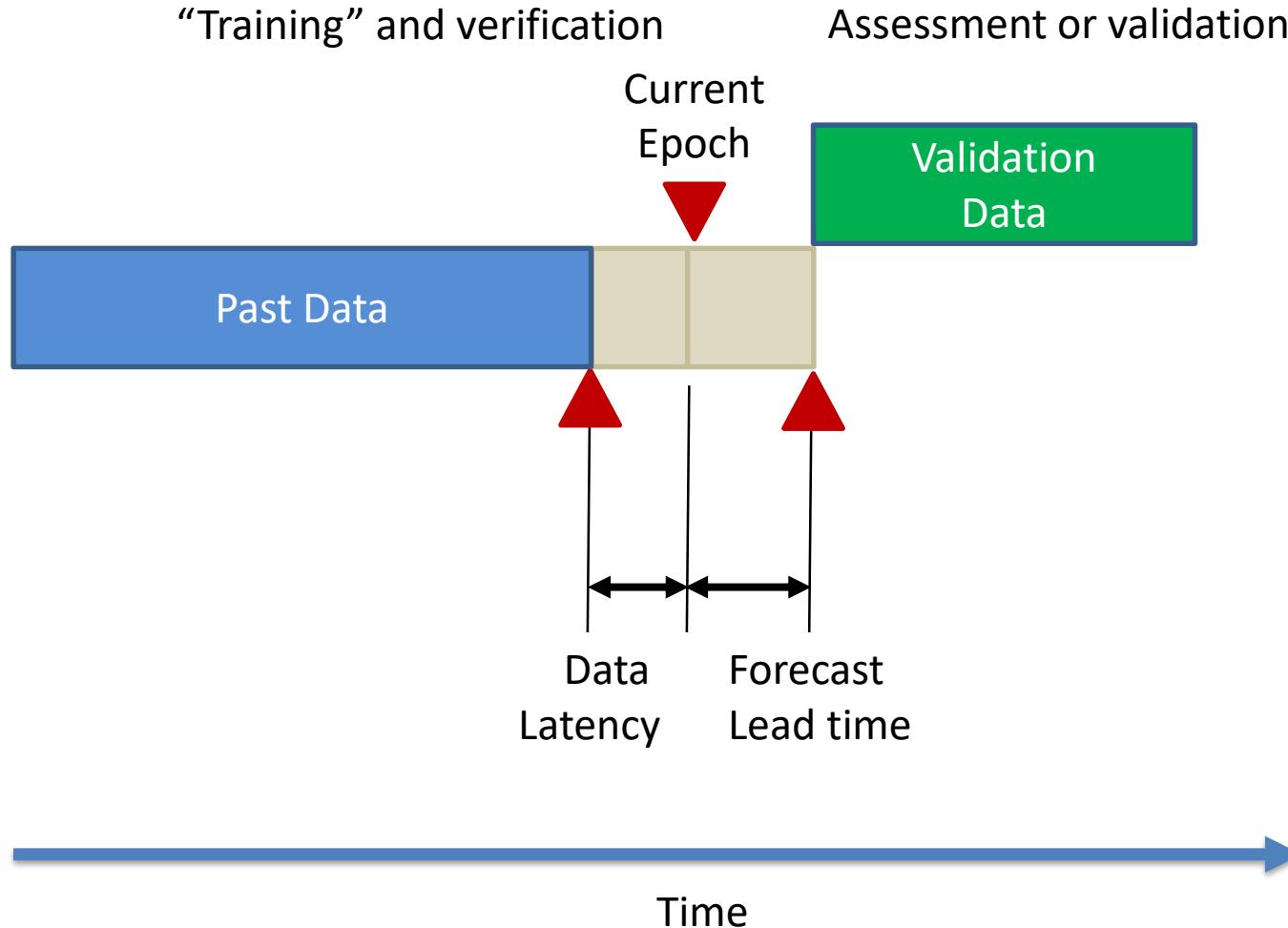
SWFT Output – F10.7 Forecast

1-day Forecast for F107(DataSet) with Data Latency of 1 day Trained with 365 Days of Data Prior to 01-May-2011 00:00:0





Time Scales for Forecast Experiments





SWFT Casts the Forecast Problem into a Statistical Framework

What quantities does the physics correlate?

What quantities are inherently more predictable?

What limits forecasts of the ionosphere-thermosphere?

- **Supervised machine learning trains a general regression model of the form**

$$y = f(x; w), x \in \mathbb{R}^n, y \in \mathbb{R}^m, w \in \mathbb{R}^d,$$

- Vector x is called independent the variable
 - Vector y is called dependent variable. In forecast applications, vector y is to be predicted using x .
 - Vector w represents model parameter
- **A collection of matched pairs $\{(x_k, y_k), k = 1, \dots, N\}$ is used to train the model to achieve optimal performance.**



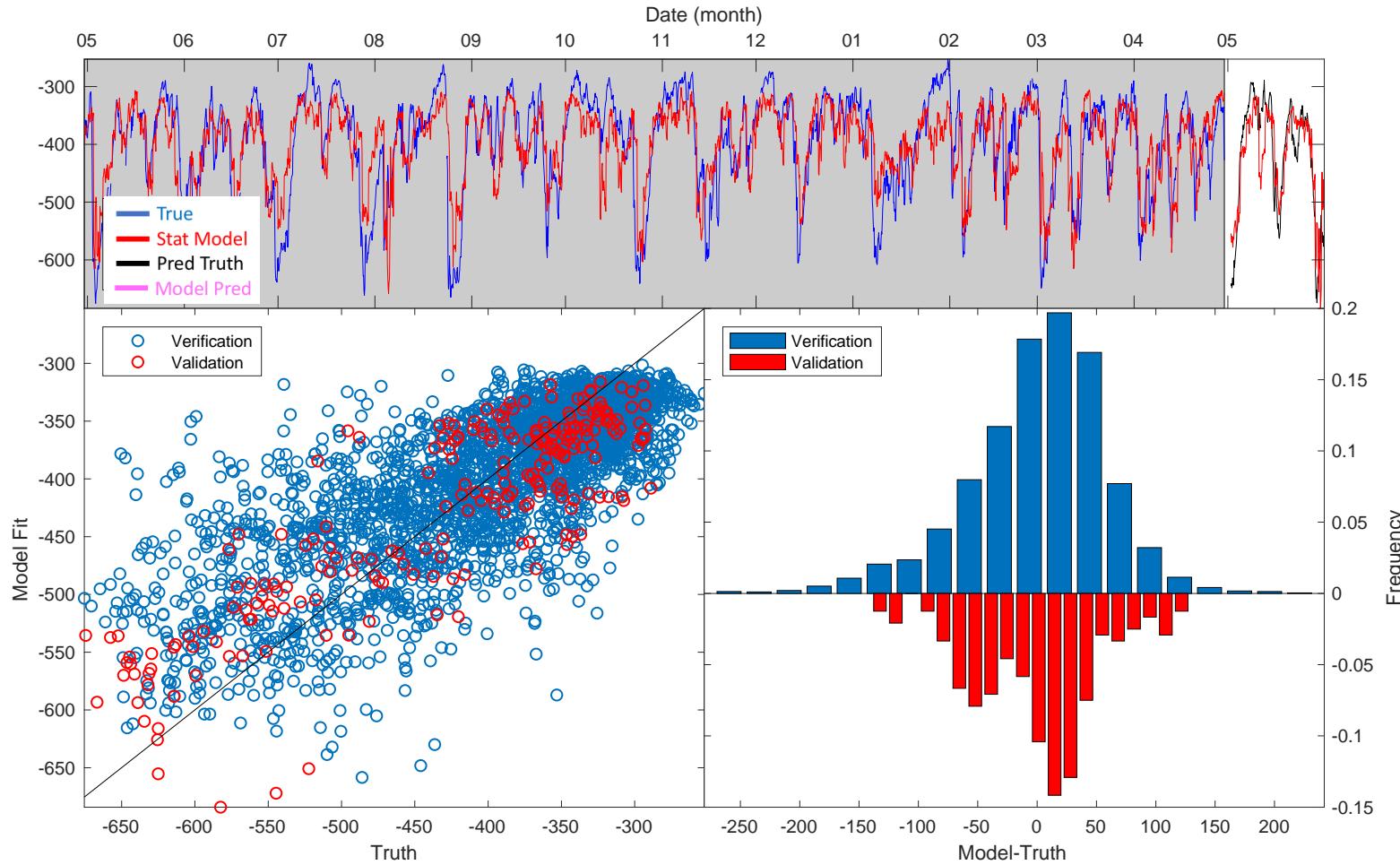
Steps in Developing a Forecast Experiment

- **Step 1: Decide on which variable to forecast.**
- **Step 2: Select independent variables:**
 - Select the variables and time history to be used.
- **Step 3: Select length of training data set and validation period:**
 - Decide what is the data latency and forecast lead time
 - Select current date
- **Step 4. Select methodology for the forecast**
 - Multilinear, logistic, random decision forest



Example of Using SWFT

1-day Forecast for Vx_velocity_Max(DataSet) with Data Latency of 1 day Trained with 365 Days of Data Prior to 01-May-2011 00:00:00



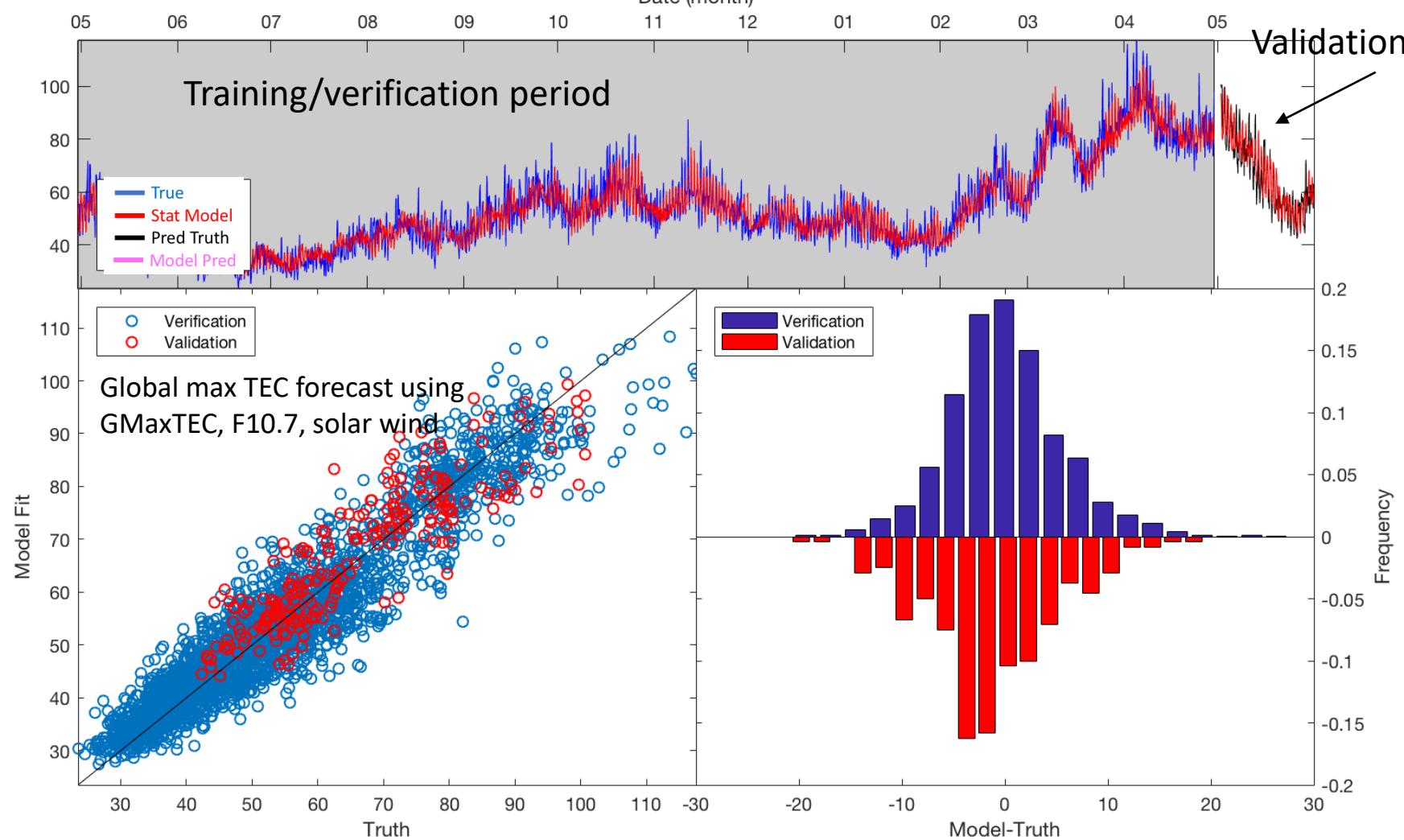


SWFT Output – Global Maximum TEC Forecast using GMaxTEC, F10.7, Solar Wind

1-day forecast

1-day latency

Trained 12 months prior to 1-May-2011



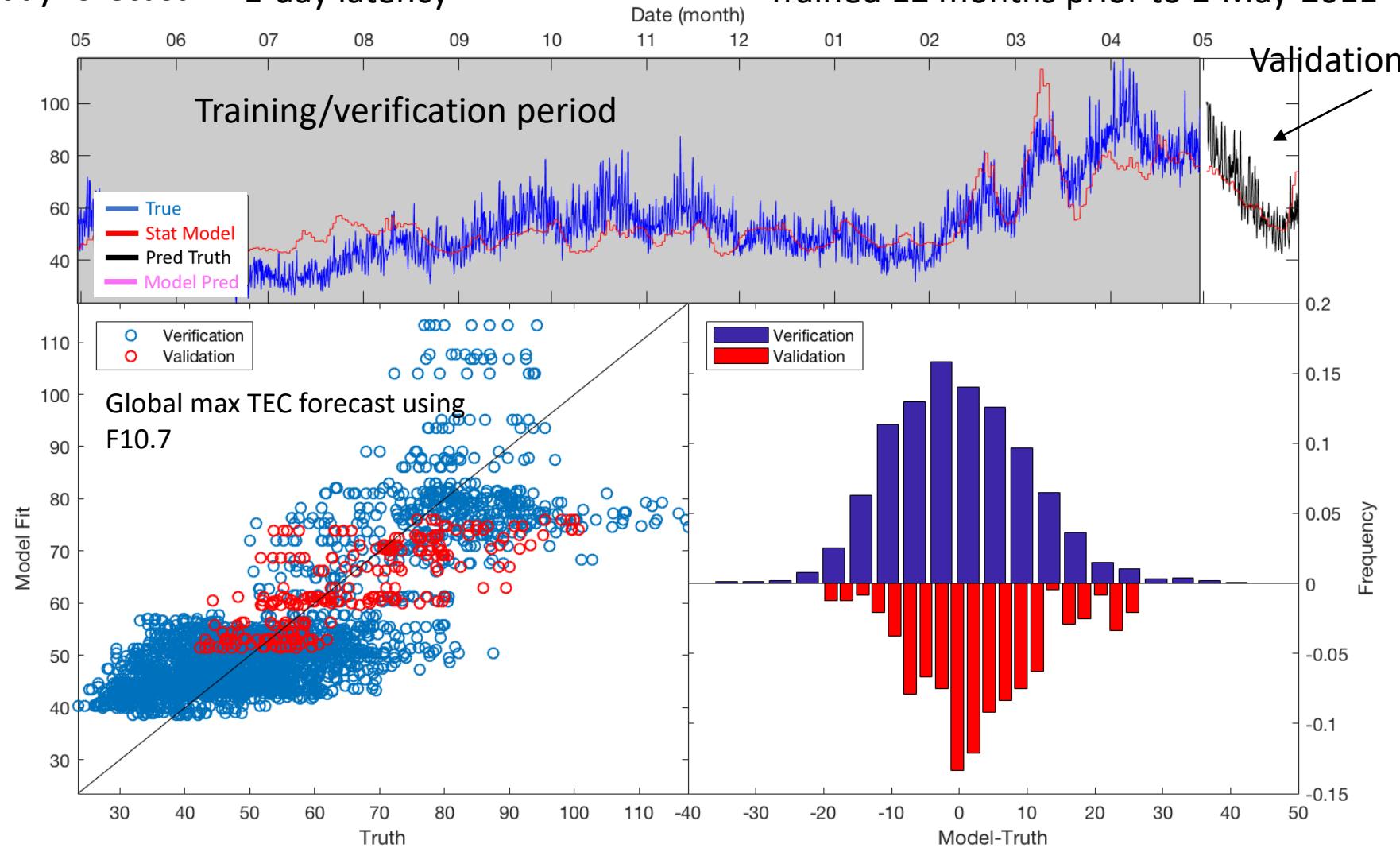


SWFT Output – Global Maximum TEC Forecast using F10.7

1-day forecast

1-day latency

Trained 12 months prior to 1-May-2011



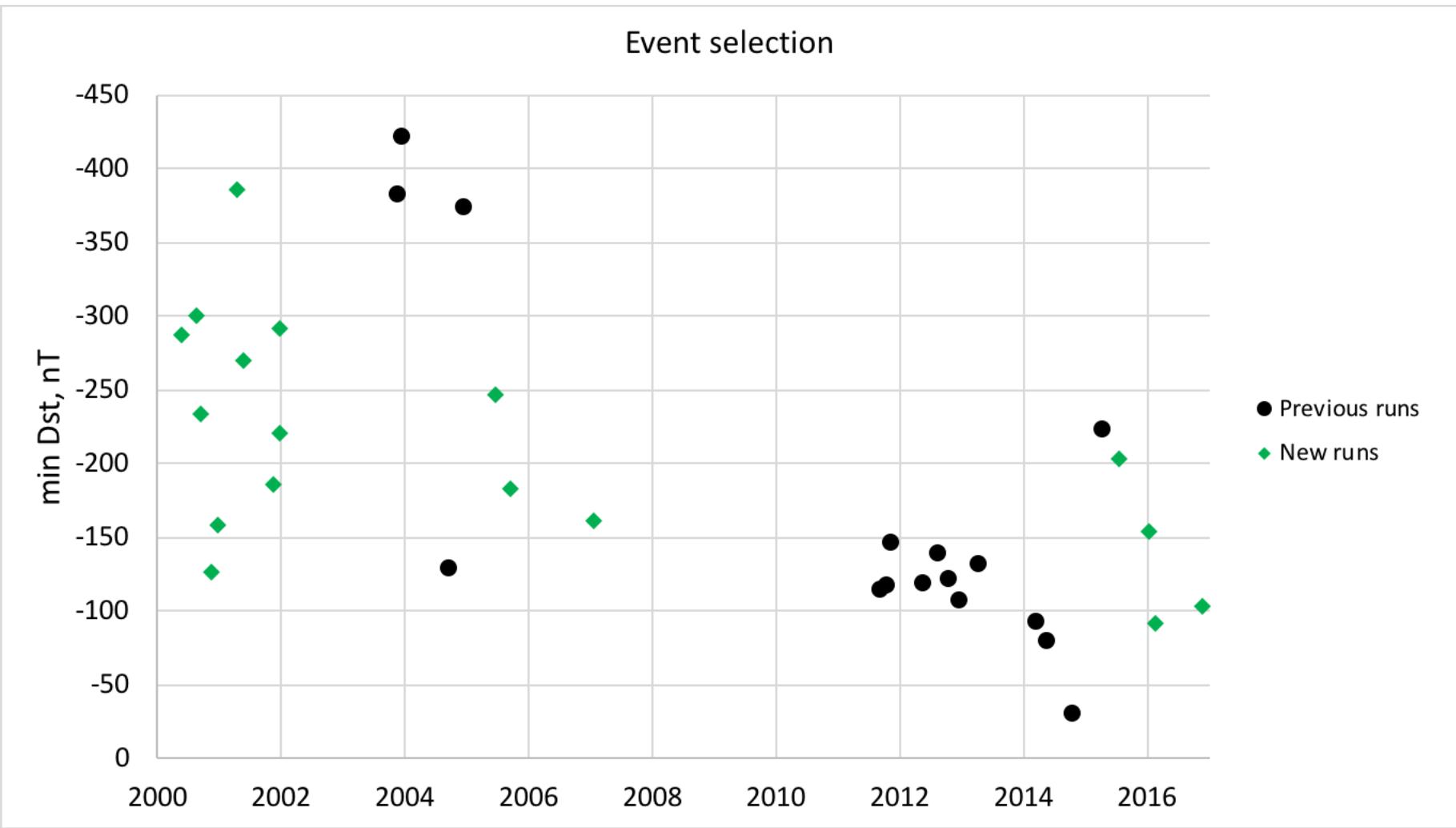


SWFT Future Development

- Additional statistical/machine learning models
- Addition of simulation output
- Addition of near solar data
 - Flare and CME events, solar wind structure ID
- Balancing training data
- More options including non-linear form of variables, hybrid variables
- Community involvement is critical
 - New data set preparation
 - Experiments with forecast strategies
 - Sharing experiences (wiki)



Generating Simulation Statistics





Summary

- CCMC has been a great partner in advancing our understanding of medium-range ionosphere-thermosphere storm forecasts
- Web-interface to beta version of Space Weather Forecast Testbed is implemented
- Forecast-mode runs using three IT models at CCMC
 - GITM, TIEGCM, CTIPe
- Continuing work on ionosphere-thermosphere forecast algorithms
 - Implementation into SWFT
- Goal: SWFT improves the community's understanding of Heliophysics simulations
- Look forward to SWFT growing organically and being of interest to a broad community
 - Physics-based community (IT and others...)
 - Statistical/machine learning community

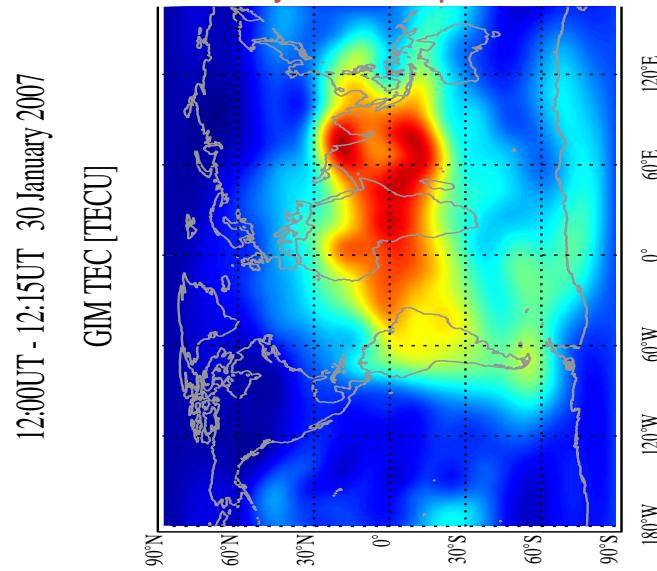


BACKUP

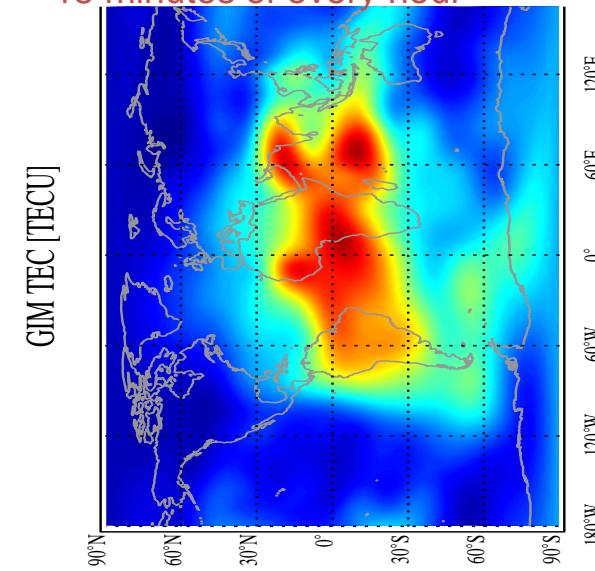
Ionosphere “Storm” Forecasts

- Based on Global Ionosphere-Thermosphere Model (GITM) [Ridley et al. 2006]
- “Forecast mode”: inputs are F10.7, solar wind from OMNI data or **ENLIL**, **CORHEL**, **SWMF** predictions for the heliosphere, driving Weimer 2005 ionospheric electrodynamics
- Alternative high latitude driving: SWMF magnetosphere and ionospheric electrodynamics
- Data product: Global Ionospheric Maps (GIM) [Mannucci et al. 1998] based on GPS-derived TEC data.

GITM: hourly TEC maps



GIM: averaged TEC for the first
15 minutes of every hour

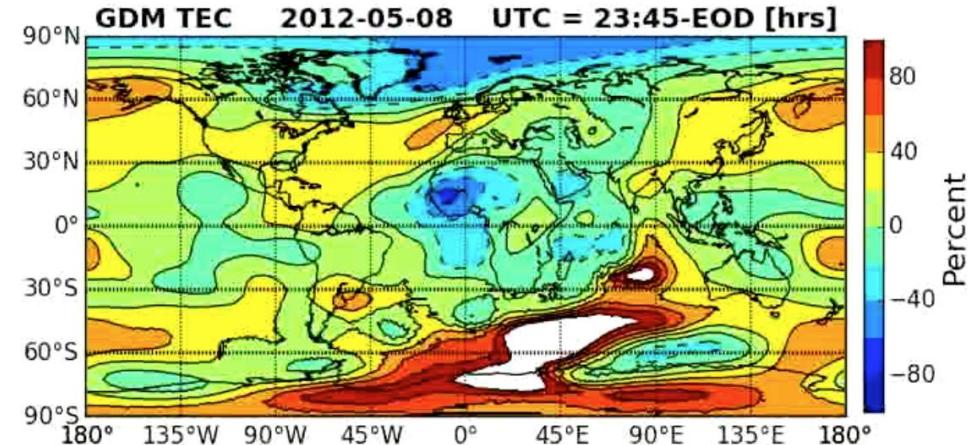
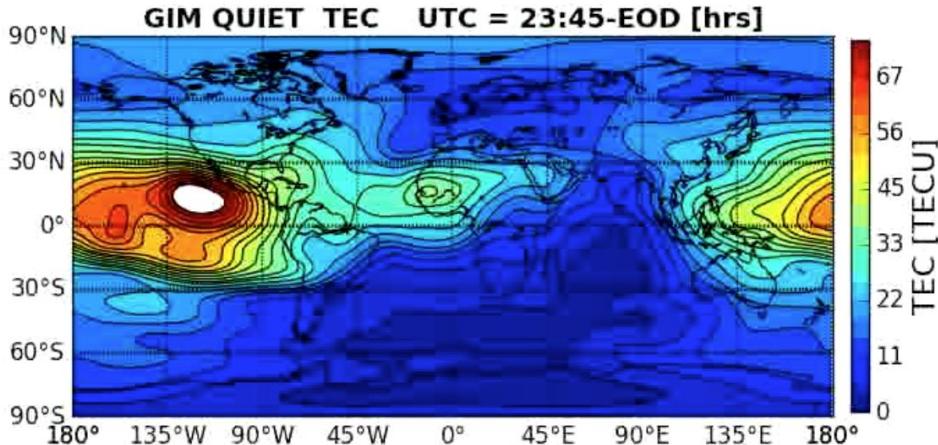
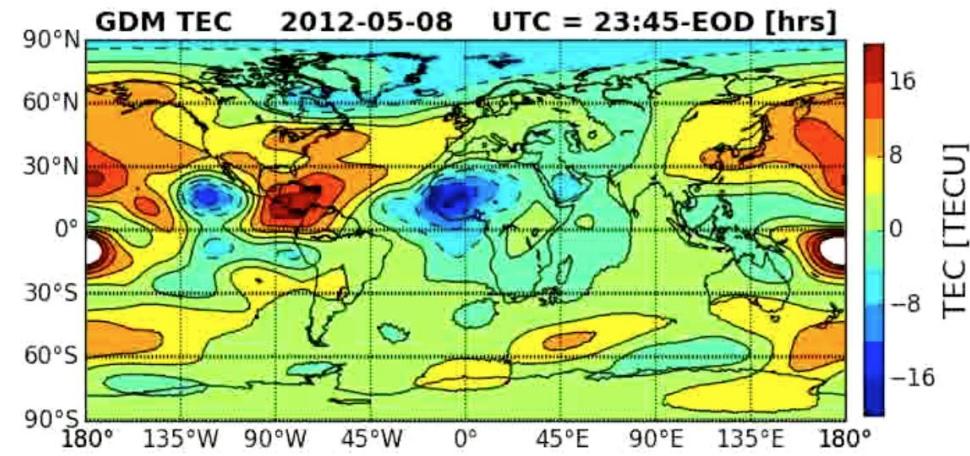
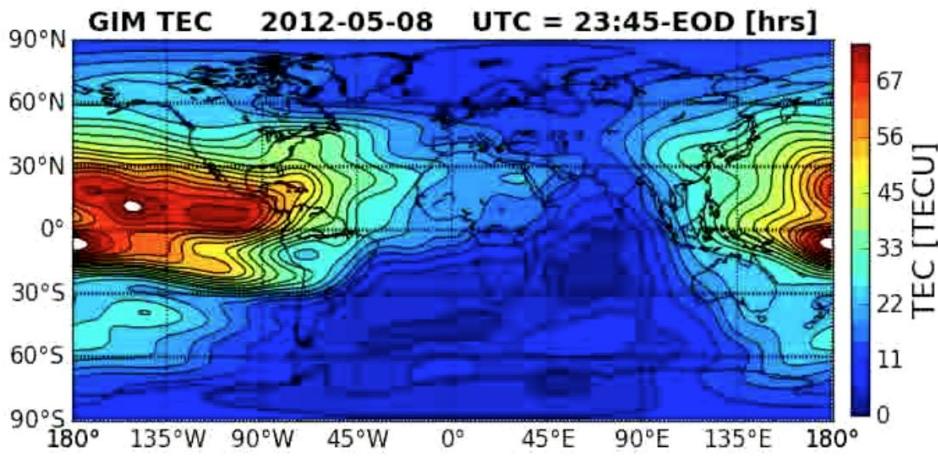


TEC maps from OMNI-driven **GITM** and **GIM** for the January High Speed Stream 2007 storm

GITM “TEC” is integrated electron density between 100 km – 600 km altitudes.



Developing Forecast Variables





Forecast Variables Definition

- Step 1: Divide the globe into grid boxes of size 30° (longitude) x 15° (latitude)
- Step 2: Compute the mean TEC within each grid
- Step 3: For **each day**, define and calculate the TEC perturbation as

GIM TEC Metric

$$dTEC_{GIM}(UT, lon, lat) = \frac{TEC_{GIM}(UT, lon, lat) - TEC_{GIM,quiet}(UT, lon, lat)}{\sigma_{TEC,GIM,quiet}(UT, lon, lat)}$$

GITM TEC Metric

$$dTEC_{GITM}(UT, lon, lat) = \frac{TEC_{GITM}(UT, lon, lat) - TEC_{GITM,quiet}(UT, lon, lat)}{\sigma_{TEC,GITM,quiet}(UT, lon, lat)} * Scale(UT)$$

where $Scale(UT) = \frac{median(TEC_{GIM,quiet}(UT, *, *))}{median(TEC_{GITM,quiet}(UT, *, *))}$

- The quiet day is selected from the days before each storm event with daily Ap < 6
- Final output: hourly $dTEC$ for every 30° x 15° grid box
- May require modification for CMEs (superstorms)

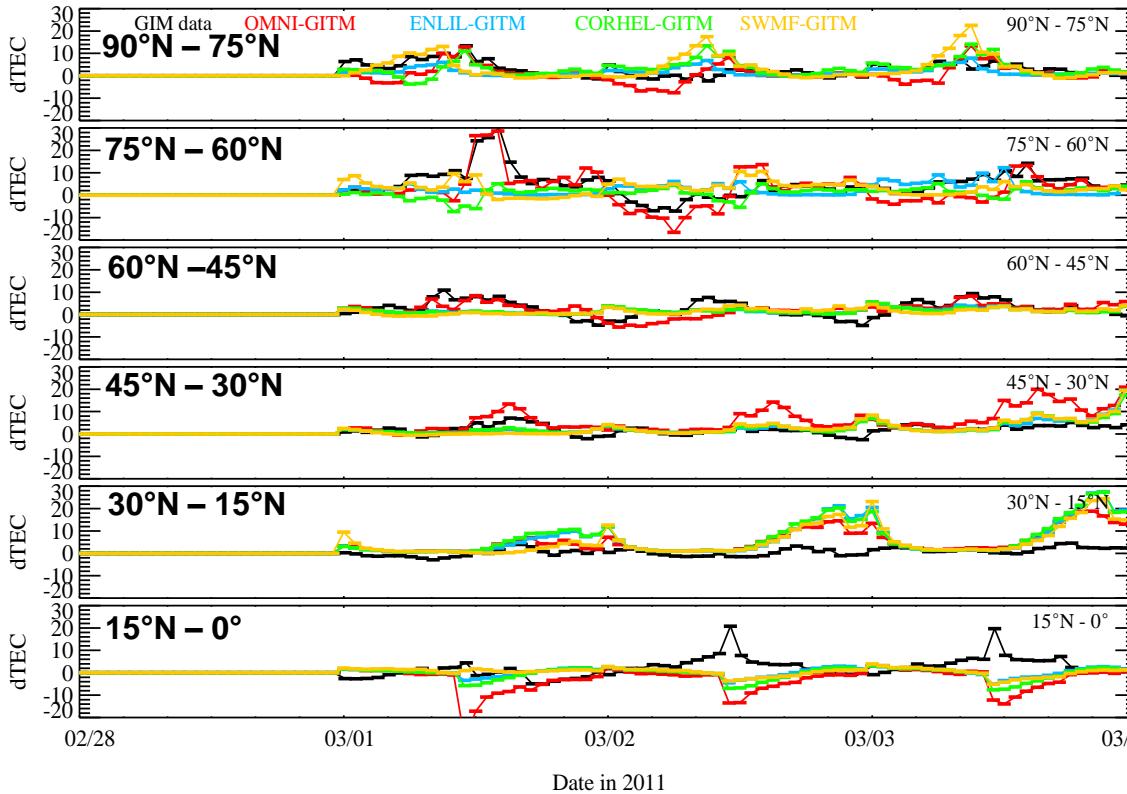
Initial forecasts will be for integrated density between 100-600 km



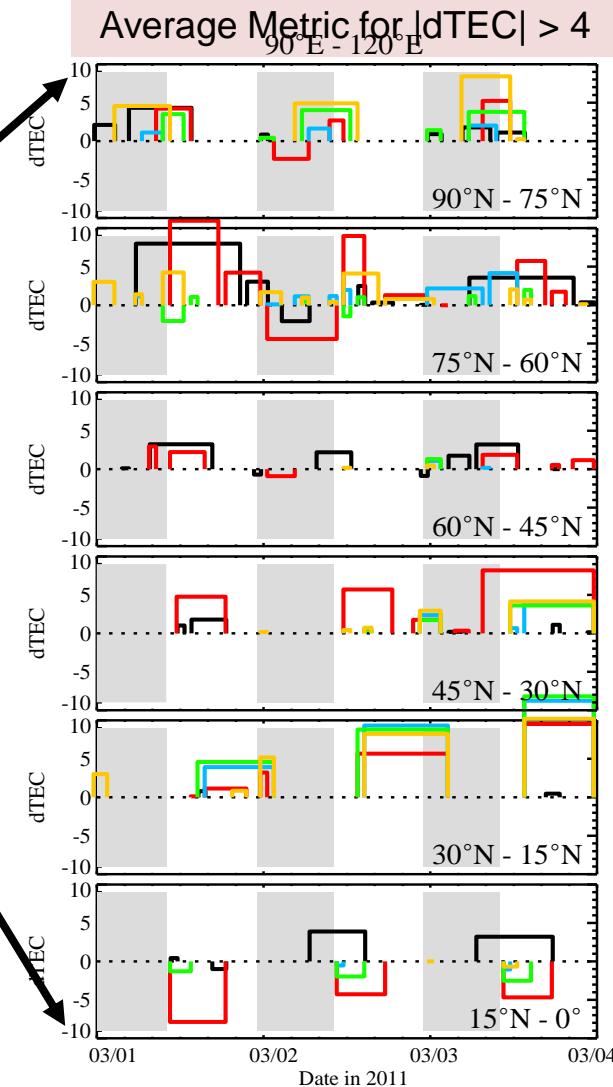
Forecast Variables Example

OMNI-GITM
ENLIL-GITM
CORHEL-GITM
SWMF-GITM

TEC Metric for the **Feb 2011 Event**
Longitude **90°E - 120°E**



Average Metric: indicates for how long and by how much $|dTEC|$ exceeds a certain level.

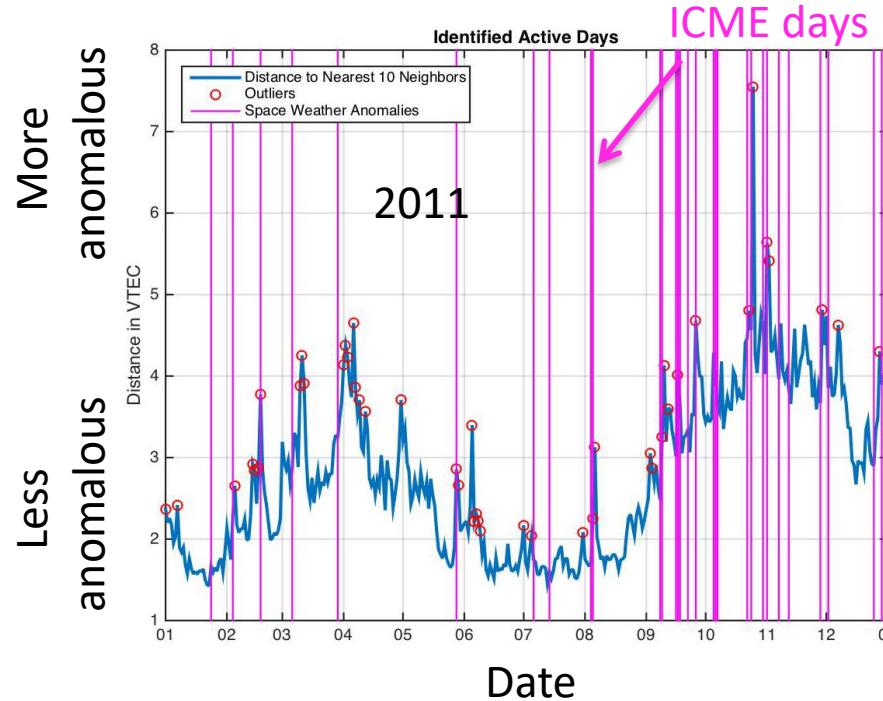


1800LT - 0600LT



Objective Analysis of “Ionospheric Anomalies”

- Cluster analysis of TEC maps identifies anomalies independently of geomagnetic conditions
- Bounds what can be achieved by solar wind driven forecasting



Wang, C., I. G. Rosen, B. T. Tsurutani, O. P. Verkhoglyadova, X. Meng, and A. J. Mannucci (2016), Statistical characterization of ionosphere anomalies and their relationship to space weather events, *J. Space Weather Space Clim.*, 6, A5–16, doi:10.1051/swsc/2015046.



CCMC Implementation

- **Establish baseline modeling chain**
 - Path towards real-time implementation
 - Variants to baseline could be implemented to produce multiple forecasts per event
- **Historical forecast runs**
 - EEGGL+AWSOM, Ansatz+ENLIL and OMNI (data) for CMEs
 - ENLIL, CORHEL, SWMF and OMNI (data) for HSS
- **Community accessible TEC forecast variables and assessment data**
- **Updated as new events occur**

*We will deliver forecast variables and related algorithms
to facilitate such a capability at CCMC*

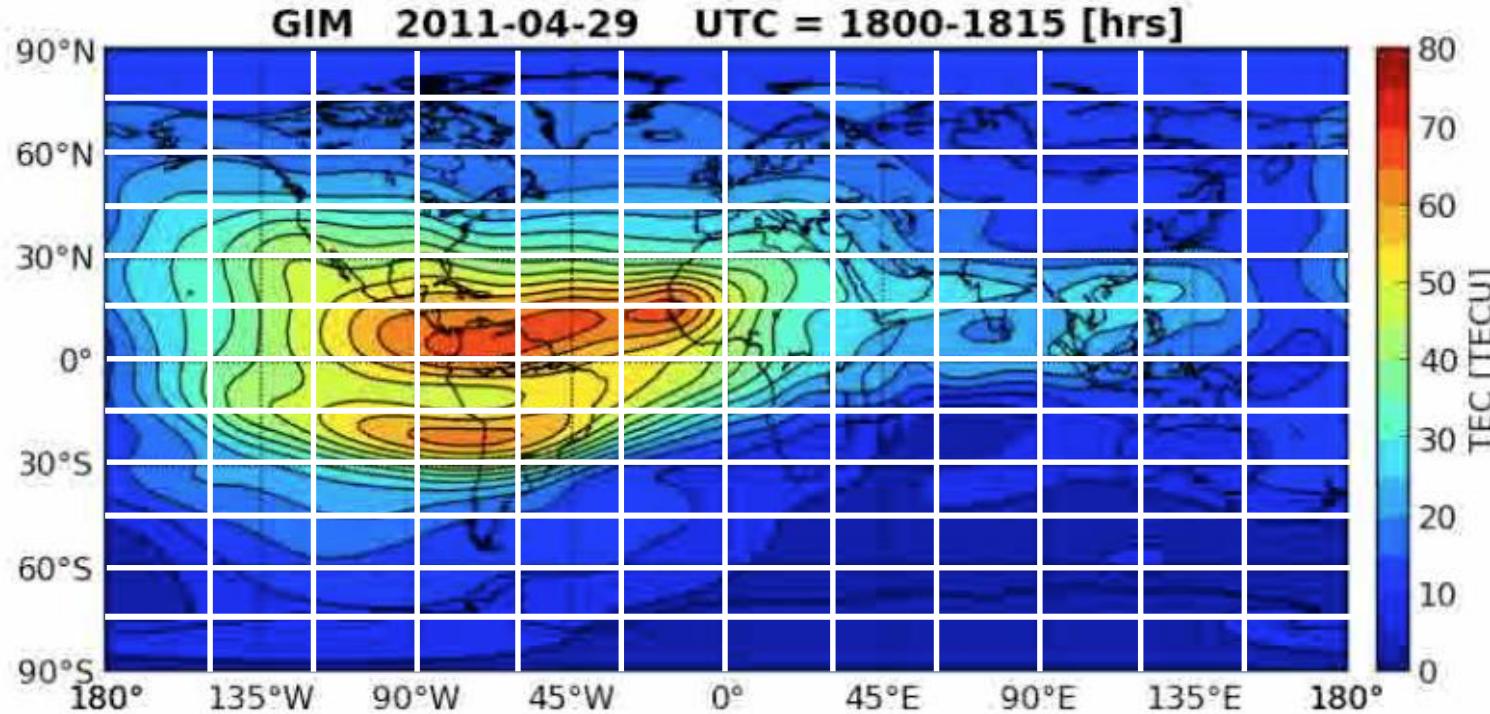
Acknowledgement: CCMC provided solar wind model runs (ENLIL, CORHEL, SWMF, ENLIL+Cone) and TIEGCM runs
See http://ccmc.gsfc.nasa.gov/community/LWS/lws_medrangestorms.php



Data-Driven Methods

Initial Approach: Focus on Total Electron Content over a Coarse Grid

A typical Global Ionospheric Map (GIM) TEC
"Data Product"



Step 1: Divide the globe into longitude-latitude grids of size $15^\circ \times 30^\circ$ lat/lon

Step 2: Develop time series of TEC metrics in each grid cell. Observations vs model

- ***Reduces the number of "predictions" from $\sim 1 \times 10^5$ (3D model) to 144 (coarse TEC grid) at each time step (e.g. hourly)***
- ***Remains complex, but is more manageable***